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Technical Report 1244
August 1988

The Efficacy of Color-Coded Symbols to Enhance Air-Traffic Control Displays

S. V. Bemis
E. A. Winer
J. L. Leeds

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152-5000

E. G. SCHWEIZER, CAPT, USN
Commander

R. M. HILLYER
Technical Director

ADMINISTRATIVE INFORMATION

This work was performed as part of Naval Ocean Systems Center's Independent Research program under program element 61152N. This work was performed by members of the Human Factors and Speech Technology Branch, Code 441, Naval Ocean Systems Center, San Diego, CA.

Released by
C.M. Dean, Head
Human Factors and Speech
Technology Branch

Under authority of
W.T. Rasmussen, Head
Advanced C2 Technologies
Division

ACKNOWLEDGEMENTS

The authors thank ACCS Don Gunja of the Fleet Area Control and Surveillance Facility (FACSFAC) in San Diego for assistance in developing the scenarios for this study. He worked closely with the authors and provided the necessary background information for implementing this research. The authors also thank Kevin Athey who created the software for this study. His efforts to create a smooth-running, bug-free computer program were greatly appreciated.

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR 1244	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Ocean Systems Center 6b. OFFICE SYMBOL (if applicable) 441	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) San Diego, California 92152-5000	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Space and Naval Warfare Systems Command 8b. OFFICE SYMBOL (if applicable) 417132	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State and ZIP Code) Washington, DC 20363	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	AGENCY ACCESSION NO.
61152N	ZT74	RR00001	DN307 408

11. TITLE (include Security Classification)

THE EFFICACY OF COLOR-CODED SYMBOLS TO ENHANCE AIR-TRAFFIC CONTROL DISPLAYS

12. PERSONAL AUTHOR(S)

S. V. Bemis, E.A. Winer, J.L. Leeds

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM TO	August 1988	41

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

color coding, shape coding, military-information displays, cognitive memory, altitude, speed

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This research tested the effect of color-coded air-traffic control displays on working memory and accuracy performance. Color, as a primary code and as a redundant code, was compared with shape coding under memory and no-memory conditions at varying density levels (5, 8, 11, and 14 symbols per display). In the shape-coded condition, symbol shapes denoted the altitude, or altitude and speed. All symbols had the same shape when color was used as a primary code. Only color denoted the altitude, or altitude and speed when color was tested redundantly.

In the memory condition, subjects were required to remember the altitude, or altitude and speed on each displayed symbol, and then sequence the planes in approach order to the landing area. Significant differences in recall accuracy occurred in the 8 and 11 symbol density displays. Compared to shape coding, color, either as a primary code or as a redundant code, significantly improved recall accuracy when altitude alone was encoded on each symbol. When both altitude and speed were encoded on each symbol, color as a redundant code significantly improved recall accuracy for the 8 and 11 symbol density levels.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL S. V. Bemis	22b. TELEPHONE (include Area Code) (619) 553-3651 22c. OFFICE SYMBOL Code 441

DD FORM 1473, 84 JAN

83 APR EDITION MAY BE USED UNTIL EXHAUSTED
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OBJECTIVE

Determine whether or not color-coded symbols enhance human memory and improve user interaction with military-information displays. Test and compare response times and accuracy on a task that requires subjects to remember encoded information on displays and, subsequently, perform a separate related task.

RESULTS

1. Color, used appropriately for coding information on displays, increases the amount of information the operators remember.

2. Color, as a single-coding dimension, aids retention when one color is used per symbol.

3. Color, as a redundant code, helps operators to remember encoded information on as many as 11 displayed symbols, even when 2 bits of information are encoded on each symbol.

4. Accuracy and response time in the combined color- and shape-coded condition were superior to the shape-coded condition alone.

5. Sensory overload appears to occur when subjects attempt to remember encoded information on 14 symbols.

6. Color, as a redundant code, can decrease response time in higher density displays.

RECOMMENDATIONS

1. Implement color-coded symbols for the information displays requiring operators to remember critical information.

2. Use only one color per symbol.

3. Require that operators of information displays not have to remember encoded information on more than 14 aircraft at one time.

4. Pinpoint exactly which information is detected, identified, and retained more effectively with color-coded symbols.

5. Follow-up on the suggestions made by this program's volunteer air controllers that the software program be investigated for use as a screening test for potential air controllers.

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INTRODUCTION

BACKGROUND

Color on military-information displays has increased dramatically during the past decade. Color has been shown by many researchers to greatly enhance search tasks. Information on the use of color-coded symbols on CRT displays for search and identification tasks falls into two categories: color coding on information displays and color coding in relation to memory. Many information displays require an operator to retain and recall displayed information, but no research has been found in the literature regarding the effect of color coding on retention and recall. Although operator performance depends heavily on working memory, the literature review also indicated that very little research had been performed on the relationship between color coding on cathode-ray-tube (CRT) displays and working memory.

Mock air-traffic control displays were selected for this study since they represent an actual application where operators must remember information encoded on continuously displayed symbols. Air controllers almost always work from their memory of inputs from various sources and from operations performed on the displayed data. On rare occasions, air-traffic control displays are not operative for seconds, and sometimes even minutes. On these occasions, a flight data strip, a hardcopy that lists current data for departing, arriving, and enroute aircraft, can be referenced. Because air controllers do not have time to obtain all the information from the flight data strip on each aircraft, the air controllers must rely upon their memory.

PURPOSE

The purpose of this research was to test the effect of color-coded displays on working memory and performance accuracy, which would, if found to have a positive benefit, improve user interaction with military-information displays. In this study, color, as a primary code and as a redundant code, was compared with shape coding. In addition, the amount of information that can be effectively color coded on a single symbol was also investigated.

APPROACH

Working memory includes cognitive units activated from long- term memory, new items, and an internal model of the immediate environment (Murphy and Mitchell, 1984). That is, working memory includes items remembered for a long time, new items just presented, and an understanding of the situation. An example for air-traffic displays follows:

(1) Air controllers learn the speed ranges of different types of aircraft during the training period. This information is stored in long-term memory. Henceforth, when a specific aircraft type is presented on the display, its respective speed range is recalled from long-term memory.

(2) New items would include altitude and route changes.

(3) According to aircraft type, initial position, and the flight path, air controllers expect a particular aircraft to occupy a specific position on the display within a fixed time frame. This is an example of an internal model of the immediate environment.

Color Coding on Information Displays

Compared to other coding schemas, color is an effective coding dimension to reduce search time in search and identification tasks (Cahill and Carter, 1976; Christ, 1975; Man Factors, Inc. 1980). Color coding is helpful when a display is unformatted, symbol density is high, the operator's task is complex, and color is logically related to the operator's task (Meister, 1984). Color is also useful for grouping related information, relocating already identified information, and assisting the operator in keeping track of critical information (Neil, 1980). Krebs and Wolf (1979) found that color does not aid the operator when a task is easy or the display is uncluttered.

Rehmann's (1984) report on the use of color displays in air-traffic control specifically mentions two studies that were performed by the Eurocontrol Experimental Center (EEC). The EEC found that color improved aircraft identification in label overlap conditions and helped controllers in judging which velocity vector applied to which track. In addition, color simplified and speeded up the sorting process.

Luder and Barber (1984) compared search and identification performance on redundant color-coded displays with performance on shape-coded monochrome displays under dual task conditions. Subjects performed a continuous compensatory tracking task on one display while periodically checking the valve state on a second display depicting the aircraft's fuel system. Subjects in the color group performed the tracking task more accurately than those in the monochrome group. Color, used as a redundant code, helped subjects search the display faster. Color coding did not assist the subjects with the identification task. Since color decreased search time but did not help subjects in the identification task, these authors concluded that color is perceptually processed in a parallel manner while shapes are processed serially. In serial processing, items are processed consecutively, one item after another. Parallel processing is defined as information that is processed simultaneously in its totality. Thus, parallel processing of information does not help identification tasks.

Two stimulus dimensions are used as coding variables in many displays. Saenz and Richie (1974) studied the effect of color in location tasks and found that performance with color as a primary code did not significantly differ from performance with color as a redundant code (color and shape). Other studies indicate that redundant coding facilitates the location of targets as opposed to coding on a single dimension (Krebs, Wolf, and Sandvig, 1978). Luder and Barber (1984) found that color as a redundant code decreased response time and improved flying performance on airborne CRT displays. Silverstein and Merrifield (1981) recommend the use of redundant color coding to retain essential information in cases where color failure or color shifts are a function of display aging. Shape as the primary encoding scheme would endure if colors faded on CRT displays.

Color Coding in Relation to Memory

Bruck and Hill (1982) used a monochromatic Naval Tactical Data System (NTDS) display and a figurative (green/red) display to study the effect of color on memory. The figurative symbology consisted of more lifelike images than the standard tactical symbology. Subjects viewed the display for 50 seconds. A map of the display was then provided for each subject. Subjects were required to recall the allegiance and type of symbols that were displayed at the marked locations on the map. There were no significant differences in accuracy between the two display conditions. In the color figurative display, the shape denoted the symbol type and color denoted allegiance. In the monochromatic Naval Tactical Display System (NTDS), shape denoted both symbol type and allegiance. Since subjects had to memorize only the shape in the NTDS display, but had to memorize both color and shapes in the figurative display, these authors suggest that subjects may have processed more information in the color figurative display than the subjects processed in the monochromatic NTDS display. If this is true, the results would indicate that the subjects in the former display condition had to perform better than the subjects in the monochromatic display condition to achieve the same mean scores since shape denoted the symbol type, and color denoted allegiance in the figurative display (Bruck and Hill, 1982).

Oda and Barker (1979) did not study color as it relates to memory but they investigated the use of color as a coding dimension to decrease the necessity for mental recall in an antisubmarine warfare (ASW) tactical display using static formats. The standard noncolor coded ASW display formats with standard numerics and graphics in the normal green color were compared with ASW formats of the same type, but with color coding added to signify the age of the displayed data. Each static display represented a point in time for an ASW airborne localization mission. The subjects determined the most likely fix positions for the target using the bearing lines that were two minutes old or less. Subjects verbally stated the selected fix positions, and the monitor circled these positions on an ASW tactical display score sheet and recorded subjects' time to analyze the format. Operator accuracy in interpreting data from the displays and time to analyze the fix positions were statistically improved with the use of color. Mean interpretation errors were 0.58 for the standard noncolor-coded ASW display test formats, but mean interpretation errors were zero for the computer-aided color-coded test format. Analysis times were reduced from 9.16 seconds for the standard format to 3.16 seconds for the color-coded display format.

SCOPE OF THE STUDY

This experiment was designed to test and compare response times and accuracy on a sequencing task. The subjects were required to number aircraft on the display according to altitude and speed in the order which the planes would approach the entry area for landing. Subjects were required to remember the encoded information, as well as execute the task based on this information. Color, as a primary code and as a redundant code, was compared with shape coding to determine the effectiveness of color coding on information retention.

The independent variables in this experiment were the following: (1) the three coding types (shape, color, color and shape); (2) the two levels of encoding (altitude, or altitude and speed); (3) the memory condition and no-memory condition; and (4)

the four density levels (5, 8, 11, or 14 symbols per display). The dependent measures were the following: (1) accuracy on the task of sequencing the aircraft for entry into the landing area with no-memory requirement; (2) recall accuracy on the task in the memory condition; and (3) the duration of time required for subjects to complete the task.

This experiment can best be explained by approaching all conditions from the second factor, levels of encoding. At one level of encoding, only altitude was encoded on the display. In the shape-coded condition, the shape of the symbol denoted the altitude level. In the color-coded condition, one color per symbol was used to denote the altitude level. In the combined color- and shape-coded condition (hereafter defined as color-shape-coded condition), there was one shape and one color per symbol.

The second level of encoding included both altitude and speed on each displayed symbol. In the shape-coded condition, the outer symbol shape remained the same for the altitude and the additional inner symbol shape denoted the speed. In the color-coded condition, the same colors denoted the altitude levels but the color of the additional lines within the symbol denoted the speed. Thus, only one color per symbol was displayed for one level of encoding while two colors were presented on each symbol for two levels of encoding. In the color-shape-coded condition, the symbol shapes were the same as in the shape-coded condition and the colors were the same as in the color-coded condition.

Rationale and Theoretical Framework

The literature indicated that color is helpful when an operator is required both to search the display and to identify symbols (Bruck and Hill, 1982; Christ, 1975; Luder and Barber, 1984; Man Factors, Inc. 1980). As previously stated, color clearly aids operators performing search tasks. The literature is contradictory on the usefulness of color when only identification tasks are involved. In order to perform the sequencing task in this study, subjects were required to search the display, identify the symbols, and remember the encoded information.

Bruck and Hill (1982) allowed 50 seconds for subjects to view the display while Christ and Corso (1983) allowed only 400 to 800 milliseconds in their research. Phillips (1974) studied presentation length and its effect on subsequent recall for randomly filled squares in a cell matrix. The results showed that recall was not as good with shorter presentations of 9 seconds compared to longer presentations of 20 seconds. Based on the above findings, the experimenters selected a 20-second viewing time for each presented display.

HYPOTHESES

Based on the previously cited literature, the following was hypothesized:

(1) Subjects would perform the sequencing task with significantly greater accuracy ($p < 0.05$) when color is used either as the primary or the redundant code than when shape coding is used alone;

(2) Subjects would remember the encoded information with significantly greater accuracy ($p < 0.05$) when color is used both as a primary and redundant code

and, consequently, subjects would perform the task more accurately than when shape coding is used alone;

(3) Subjects' response time would be significantly shorter ($p < 0.05$) in both the color- and color-shape-coded conditions than with shape-coded symbols in the higher density levels.

METHOD

SUBJECTS

The 14 subjects included 6 male and 6 female naval air controllers from the Fleet Area Control and Surveillance Facility (FACSFAC) in San Diego and 1 male and 1 female civilian scientist from the Naval Ocean Systems Center. Subjects' ages ranged from 20 to 36 years with a mean age of 27 years. Subjects qualified for the experiment by passing a color vision test and a visual acuity test with 20-20 corrected vision.

EQUIPMENT

A Masscomp multiuser, Model 5600 unix-based minicomputer system with realtime data acquisition capability was used for producing the symbology and recording the data. An Aurora workstation, a 19-inch color monitor with a resolution of 1152 × 910 pixels, and an extended graphics capability was used to display the symbology to the subjects. A workstation mouse was provided for subjects to select displayed symbols. Symbol size for all coding types was 0.22 inch (5.59 mm). Line thickness was 0.012 inch (0.3 mm) for all symbols in all conditions. Subjects were seated in front of the display with a 22-inch eye-to-display distance. At this distance, the visual angle was 34 minutes-of-arc.

SCENARIO DEVELOPMENT

The scenarios for this experiment were developed with the aid of ACCS D. E. Gunja of FACSFAC, San Diego (Personal communication, 19 February 1987). These scenarios were simulated in the 48 displays used in this experiment. During scenario development, symbol locations were assigned randomly on each display by the computer. When this random assignment resulted in overlapping symbols, the programmer manually adjusted the symbols. Thus, symbol overlap was eliminated as a confounding variable for this study. The four altitude levels were assigned to symbols randomly except for the provision that each altitude level had to be represented at least once on each display. For two levels of encoding, the four speed levels were also assigned to symbols randomly except for the requirement that each speed interval had to be presented at least once on each display. All subjects viewed the same scenarios.

RESEARCH DESIGN

The experimental design was a 3×2×2×4 (Coding Type × Level of Encoding × Memory/No-Memory conditons × Density Level) repeated measures factorial design (figure 1). The subjects' task was to give priority to the aircraft according to altitude and speed for entry into the landing area represented by two parallel lines on the screen. Figure 2 shows a sample display. The three coding types, two levels of encoding, memory/no-memory conditions, and four density levels were within-subject variables. Each display condition had one coding type and either one or two levels of

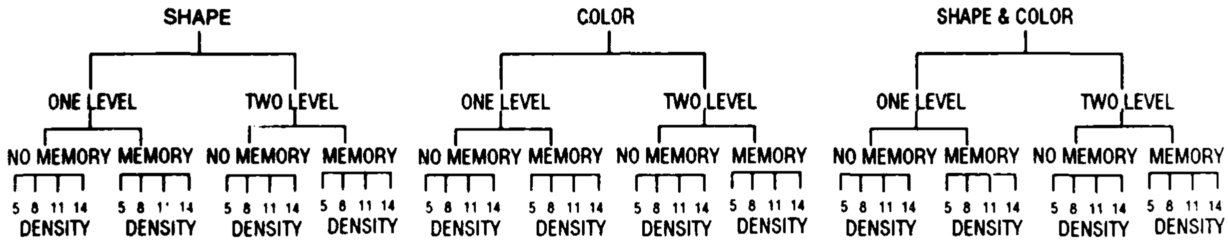

Figure 1. A 3×2×2×4 repeated measures experimental factorial design.

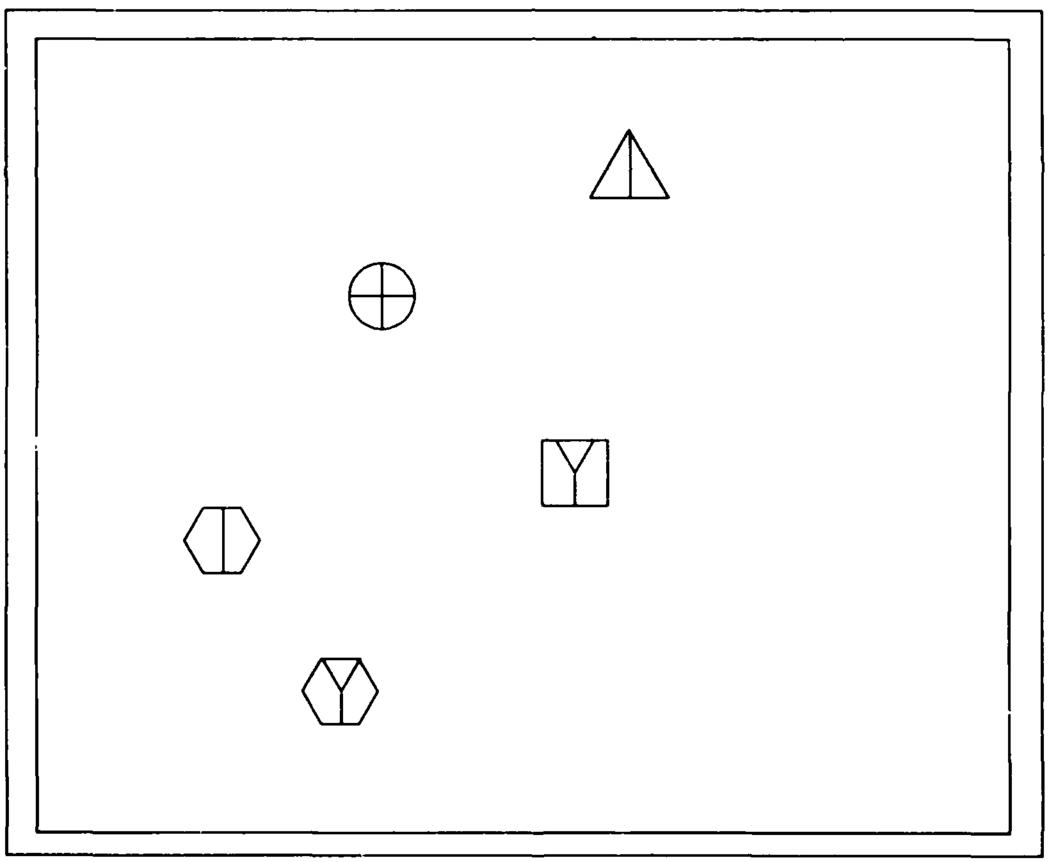

Figure 2. Sample display of five symbols, two-dimensional shape coding.

encoding. Each of the following six display conditions was subdivided into a no-memory and a memory condition:

(1) Symbols were geometric shapes in the first display condition. Subjects were tested on shape coding in one dimension. Only altitude was encoded on the display. Circles [○] represented aircraft flying below an altitude of 10,000 feet. Triangles [△] represented aircraft at altitudes of 10,001 to 20,000 feet. Squares [□] denoted aircraft at altitudes of 20,001 to 30,000 feet. Hexagons [⬡] represented aircraft flying above 30,000 feet. As the number of corners increased on the symbols (from circles, triangles, squares, to hexagons) the altitude level rose.

(2) In the second display condition, shape coding was also used but subjects were tested on two levels of encoding. Both speed and altitude were presented on the display. The same shapes in the first condition denoted the same altitude levels in this display condition. Speed was estimated through a symbol placed inside the altitude indicators. A single vertical line [|] indicated that the aircraft's speed was less than 200 knots. Three lines [Y] within the altitude symbol indicated that the craft was flying at 201 to 300 knots. Four lines [+] within the symbol indicated that the aircraft was flying at 301 to 400 knots. An asterisk [*] denoted that the aircraft's speed was greater than 400 knots. As the number of lines increased within the symbol, the speed increased. The outer symbol denoted altitude and the inner symbol denoted speed. Figure 3 shows the 16 different types of symbols that were presented on the display.

(3) In the third display condition, subjects were tested on color coding with one level of encoding (altitude only). All symbols were the same shape [diamonds (◇)]. One color per symbol denoted the craft's altitude. A total of four colors was

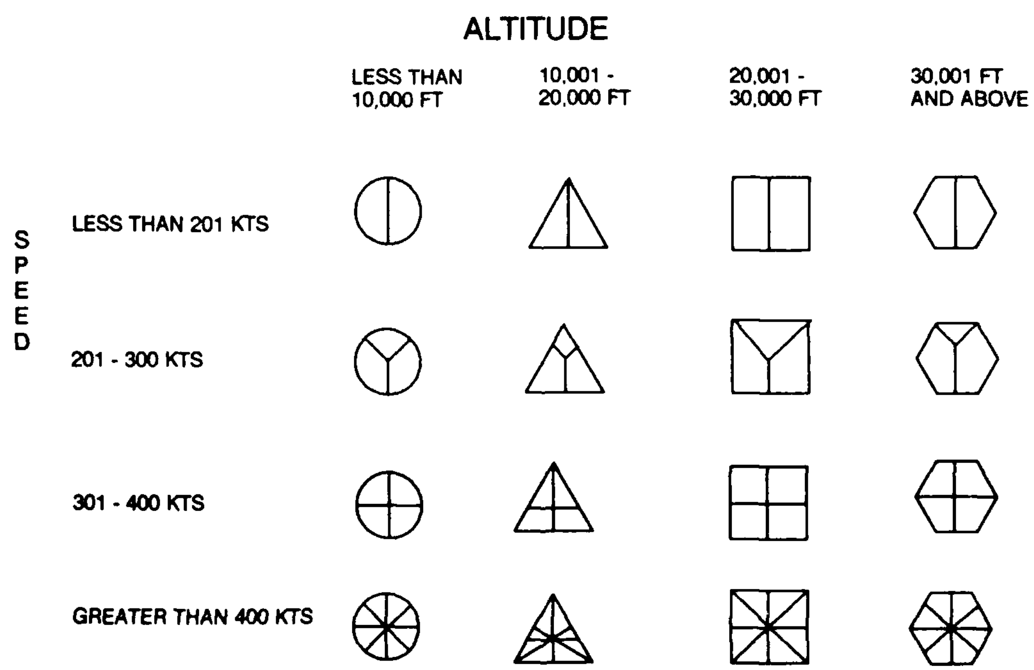

Figure 3. Shape-only symbols for two dimensions.

presented on each display. The color red denoted aircraft at altitudes less than 10,000 feet. Orange represented aircraft at altitudes of 10,001 to 20,000 feet. Yellow indicated that the aircraft's altitude was 20,001 to 30,000 feet. White represented aircraft flying at altitudes above 30,000 feet. These colors were selected so that light colors would be the ones used for the higher altitudes.

(4) Color coding was also used in the fourth display condition but subjects were tested on two levels of encoding. Both altitude and speed were encoded on the display. Two colors appeared on each symbol so that a total of eight colors was presented on each display. The colors on the diamonds denoted altitude as in the third condition. The color of the lines within the diamond [◇] denoted the speed. Purple lines indicated the aircraft's speed was less than 200 knots. Blue represented aircraft flying from 201 to 300 knots. Cyan denoted the aircraft's speed was 301 to 400 knots. Light green indicated the aircraft's speed was greater than 400 knots. These colors were selected so that light colors would denote higher speeds.

(5) In the fifth display condition, both color and shape coding were used. Color was used as a redundant code. Subjects were tested on one dimension only. Shapes and their connotations were the same as those in the first display condition. The colors and their connotations were the same as those in the third display condition. Thus, each symbol had one shape and one color.

(6) In the last display condition, both color and shape coding were used with subjects being tested on two dimensions (altitude and speed). Symbol shapes and their connotations were the same as in the second display condition. Colors and their connotations were the same as those in the fourth display condition. Both the shape and the color on the outer symbol denoted altitude while both shape and color on the inner symbol denoted speed.

Table 1 shows the order of presentation for all subjects. Subjects viewed all the displays in one display condition before displays in another display condition were presented. Shape coding was tested in the first and second display conditions. Color was tested as a primary code in the third and fourth display conditions and as a redundant code in the fifth and sixth display conditions. Subjects were tested with one coding type before displays with another coding type were presented. For example, if a subject first was tested in display condition 2 (shape coding at two levels of encoding), display condition 1 (shape coding at one level of encoding) immediately followed. Memory and no-memory conditions were counterbalanced within display conditions. Half of the subjects performed the task in the no-memory condition first while the other half performed the task in the memory condition first. Display density was composed of 5, 8, 11, and 14 symbols per display. Each display composition was randomly presented one time for the memory condition and one time for the no-memory condition in all display conditions. Each subject viewed 16 displays for each coding type. A total of 48 displays was presented to each subject for all display conditions.

Table 1. *Order of condition presentation to subjects.*

Sub #	1st Coding Type	2nd Coding Type	3rd Coding Type	Level First	Memory/No Memory First
1	Shape	Color	C-S*	One	No Memory
2	Shape	C-S	Color	One	Memory
3	Shape	C-S	Color	Two	Memory
4	Shape	Color	C-S	Two	No Memory
5	Color	C-S	Shape	One	No Memory
6	Color	Shape	C-S	One	Memory
7	Color	Shape	C-S	Two	No Memory
8	Color	C-S	Shape	Two	Memory
9	C-S	Shape	Color	One	No Memory
10	C-S	Color	Shape	One	Memory
11	C-S	Color	Shape	Two	No Memory
12	C-S	Shape	Color	Two	Memory
13	Shape	C-S	Color	One	No Memory
14	Color	C-S	Shape	One	Memory

* = Color-Shape Condition

PROCEDURE

Each subject was administered the Armed Forces Clinical Visual Acuity Test and a color vision test using the Dvorine Color Plates. In addition, each subject was required to identify all eight colors used in this experiment. These colors were displayed as lines on the CRT and subjects verbally identified each color. Each subject read written instructions and viewed a 10-minute videotape depicting the sequencing task before training began for the display condition presented first. The written instructions are presented in Appendix A. Original figures associated with the written instructions are retained by the author and not included in the appendix. Although the instructions emphasized accuracy performance, subjects were aware that response times also were being measured.

The training sessions and the tests were presented in a darkened room with only a steady distant noise in the background. Before subjects were tested in each display condition, the symbols were displayed on the screen and subjects were instructed

to learn the type of coding that would be used in the next testing session. When subjects had learned the symbols and their connotations, the subjects pressed a button on the mouse. Subjects then had to correctly identify three random presentations of each symbol with 100-percent accuracy. To identify each symbol, the subjects used the mouse to place the cursor in one of the labeled boxes on the right side of the display. Next, the subject pressed a button on the mouse (figure 4). Subjects then completed two practice scenarios. After subjects successfully completed the training session, the test began. When subjects finished one test, the symbols for the next display condition were displayed on the monitor for the subjects to learn. The experimenters had no contact with the subjects during the six training sessions and tests.

Subjects viewed a static display for 20 seconds for each test condition. Immediately following the display, the subjects were tested. Two parallel lines, 2 1/4 inches apart, located perpendicular to the righthand edge of the CRT, represented the entry to the landing area. Subjects used the aircraft's speed and altitude as criteria for sequencing the aircraft for approach order. Altitude had priority over speed. Aircraft with the lowest altitude received top priority. Aircraft with the highest altitude received the least priority. When two or more planes were at the same altitude, the aircraft were given priority according to the speed within this altitude level. The

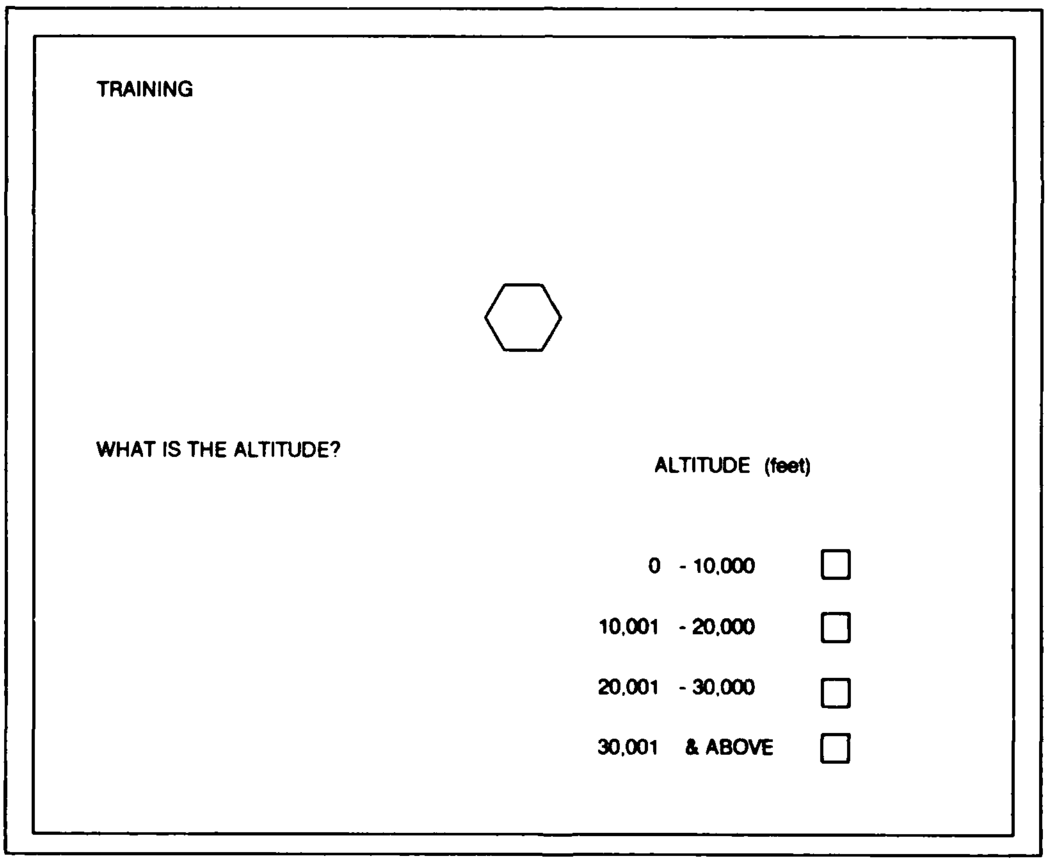

Figure 4. Sample display for training session.

faster the speed, the higher the priority. If two or more craft had the same altitude and speed (or two or more craft had the same altitude in one level of encoding), then proximity to the right side of the display had priority. Subjects moved the mouse across the mouse pad to place the cursor on each symbol. After placing the cursor on a symbol, subjects pressed a button on the mouse which inserted the next number in the sequence by the aircraft.

In the no-memory condition the coded symbols remained visible. After 20 seconds, the computer beeped to indicate the subject should begin the task of numbering the aircraft in the correct order for entry to the landing area. After 20 seconds in the memory condition, the symbols were replaced with filled diamonds at the sound of the beep. Subjects were required to remember the aircraft's altitude and speed to sequence the planes in approach order.

Subjects had two options for error correction. The capability was provided for subjects to erase up to three numbers on the last three sequenced aircraft. For example, if a subject had already sequenced 6 aircraft on a 14-symbol density display and found an error in the sequence, the subject could erase the incorrect numbers by moving the cursor to the last sequenced aircraft and pressing the button on the mouse. In this example, the number 6 was then removed. The subject then had the option to erase number 5, then number 4, and then renumber the craft in the correct order. Afterwards, the subject continued sequencing all remaining aircraft. After all aircraft were sequenced on the display, the subjects were offered the second option to resequence all the aircraft. A question, along with "yes" and "no" labeled boxes, was displayed on the screen. Subjects were asked if they desired to resequence all aircraft. Subjects responded by placing the cursor in the "yes" or "no" box. If subjects selected "yes," they resequenced the aircraft and a second number appeared beside each symbol. *If subjects selected "no," or if they completed the sequencing task for the second* time, the next display was presented.

Subjects received feedback on their total scores when testing was finished. The total number of aircraft correctly sequenced in all scenarios was displayed along with the total number of planes that were sequenced in all display conditions. After completing the experiment, subjects' preference for coding type and additional comments were obtained through a questionnaire.

DATA COLLECTION

The computer recorded the correct sequence of the aircraft for entering the landing area and the sequence selected by the subject for each display that was presented. The number of errors per display were computed for each subject. The computer recorded response time for completing the sequencing task on each display. Mean errors and mean response times for each subject were computed.

RESULTS

Results are presented in four sections. Accuracy scores are analyzed first for the task of sequencing the aircraft in approach order. The percent correct on each display was computed. These percentages were used in the analysis of variance. In

the second section, response times for completing each sequencing task are analyzed. Results of the correlational analysis along with the results of the subjective questionnaires are presented in the third section. The final section summarizes the major findings of this research.

ACCURACY

A four-factor within-subject analysis of variance was performed on the percent correct for the task of sequencing aircraft for entry to the landing area (table 2). Results in this section are presented in the following order:

Table 2. Analysis of variance table for accuracy scores.

Source	df	SS	MS	F	P
Coding (C)	2	0.33	0.16	2.02	0.1530
Error	26	2.09	0.08		
Level (L)	1	3.34	3.34	76.62	0.0000
Error	13	0.57	0.04		
Memory (M)	1	15.87	15.87	235.74	0.0000
Error	13	0.88	0.07		
Density (D)	3	13.04	4.35	146.98	0.0000
Error	39	1.15	0.03		
C × L	2	0.50	0.25	5.99	0.0072
Error	26	1.08	0.04		
C × M	2	0.10	0.05	1.68	0.2055
Error	26	0.75	0.03		
C × D	6	0.19	0.03	1.62	0.1525
Error	78	1.55	0.02		
L × M	1	0.42	0.42	7.18	0.0189
Error	13	0.76	0.06		
L × D	3	1.22	0.41	15.58	0.0000
Error	39	1.02	0.03		
M × D	3	5.24	1.74	35.63	0.0000
Error	39	1.91	0.05		
C × L × M	2	0.01	0.0006	0.19	0.8278
Error	26	0.93	0.04		
C × L × D	1	0.16	0.03	1.07	0.3879
Error	13	1.97	0.03		
C × M × D	1	0.45	0.08	2.21	0.0500
Error	13	2.64	0.03		
L × M ×D	3	0.73	0.24	7.53	0.0004
Error	39	1.26	0.03		
C × L × M × D	6	0.59	0.10	2.89	0.0135
Error	78	2.64	0.03		

C = Coding L = Level M = Memory D = Density

(1) Significant differences in accuracy scores between coding types within levels of encoding and density levels are presented first. No distinction is made between memory and no-memory scores;

(2) Significant differences in accuracy scores between coding types in the memory condition follow; and

(3) Other significant findings unrelated to coding type are then presented.

The main effect of coding type was not significant. Overall, there was little difference in mean accuracy scores between coding types (shape = 79 percent; color = 77 percent; color-shape condition = 82 percent). However, a significant interaction was found between coding type and level of encoding. Newman-Keuls comparison tests showed that mean accuracy scores between the color condition (84 percent) and the shape-coded condition (81 percent) had borderline significance when only altitude was encoded on the displayed symbol (one level of encoding). No significant differences existed between the color condition (84 percent) and the color-shape-coded condition (83 percent). When both altitude and speed were encoded on the displayed symbol (two levels of encoding), results were reversed. Mean accuracy scores were significantly lower in the color condition (58 percent) than in either shape alone (69 percent) or the color-shape-coded condition (71 percent).

Newman-Keuls comparison tests were performed on mean accuracy scores for all relevant interactions between factors in the statistical analysis. Significant differences between coding types occurred within the memory condition in the 8- and 11-symbol density levels. Figure 5 shows that mean recall accuracy was significantly more accurate when both color and shape coding were used to encode information for displays containing 8 or 11 symbols for both levels of encoding. The data in figure 6 further show that color coding was superior to shape coding when only altitude was presented on the display. A large difference in mean recall accuracy existed between the color-shape-coded condition (57 percent) and color alone (29 percent) in the 11-symbol density displays when both altitude and speed were encoded on the displayed symbols. Also, shape alone (42 percent) was superior to color alone (29 percent) which was reversed from the scores at one level of encoding when only altitude was presented on the display. Subjects remembered the encoded information and performed the task of sequencing the aircraft equally well with all coding types in both one and two levels of encoding when the display composition consisted of five symbols. Recall was poor for all subjects with all coding types when the displays contained 14 symbols.

Other significant findings unrelated to coding type are now presented. The main effects of level of encoding, memory/no-memory conditions, and density level were significant across all coding types. All subjects performed the task more accurately with one level of encoding than with two levels of encoding. As expected, subjects performed the sequencing task more accurately in the no-memory condition than in the memory condition where subjects were required to remember the altitude, or altitude and speed of craft to perform the sequencing task. Figure 7 shows that as the numbers of symbols increased on the display, accuracy decreased.

Subjects had the option of resequencing the aircraft on each display. Additional analyses of variance were performed on the percent correct and response time with subjects' second trials being substituted where applicable. These scores had no

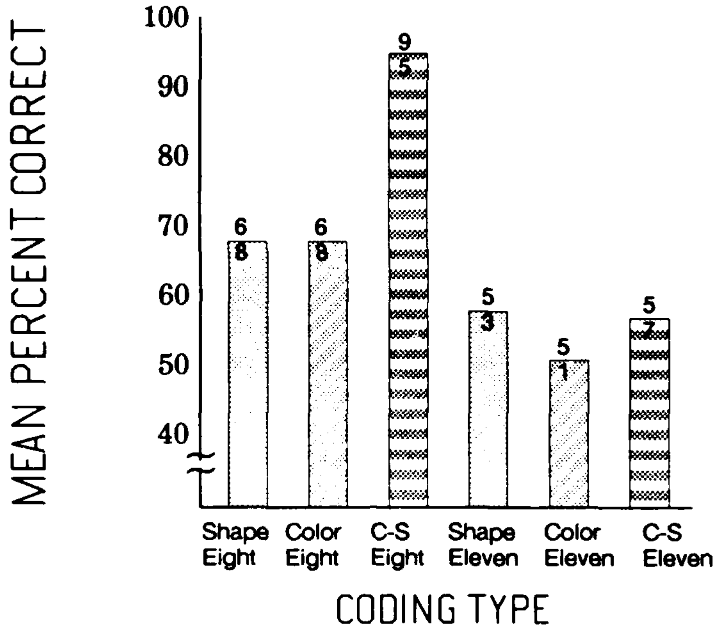

Figure 5. Mean percent correct as a function of coding type at the 8- and 11-symbol density levels in the memory conditions across both levels of encoding.

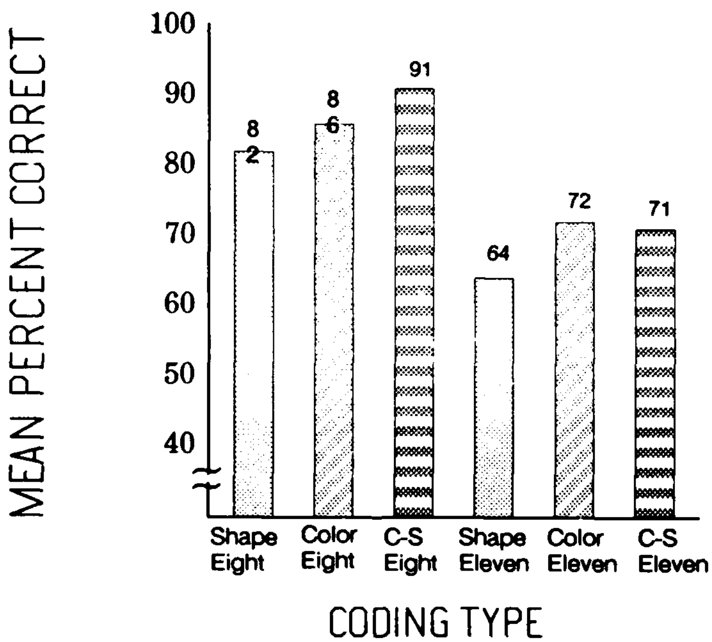

Figure 6. Mean percent correct as a function of coding type at the 8- and 11-symbol density level in the memory condition for one level of encoding.

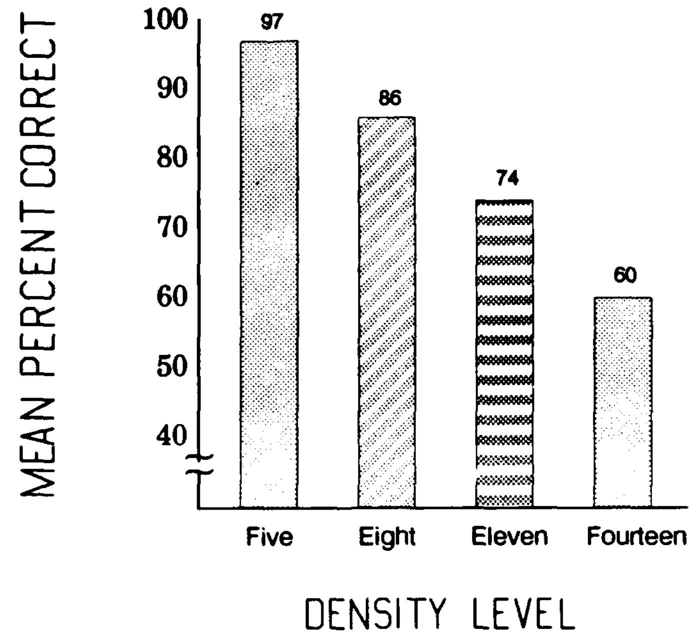

Figure 7. Mean percent correct as a function of density level.

significant impact on the results and were not included in the final analysis since subjects only used the option in six percent of the test displays.

RESPONSE TIME

A 3×2×2×4 analysis of variance was performed on the length of time required by subjects to complete the task of sequencing the aircraft on each display (table 3). The main effect for coding type was not significant. Newman-Keuls tests were performed on all significant interactions between factors. The two-way interaction between coding type and level of encoding was significant. This two-way interaction must be interpreted with caution, however, because of the significant three-way interaction for coding type, level of encoding, and density level. Overall, these results showed that significant differences in response time between coding types occurred in the 14-symbol density displays. There were no significant differences in response time between coding types within the other three density levels (5, 8, or 11 symbols presented on the display). The following describes the significant differences found between coding types for the 14-symbol display compositions. Figure 8 shows the mean response times for the interaction between coding type and level of encoding in the 14-symbol-density level. Response times were significantly reduced for the color-coded condition when altitude alone was encoded on the symbol. The opposite effect occurred when both altitude and speed were color coded on the symbol. The color condition had the highest mean response time for two levels of encoding.

The three-way interaction for coding type, memory/no-memory conditions, and density levels was significant. Significant differences were found to exist between

Table 3. Analysis of variance table for response times.

Source	df	SS	MS	F	P
Coding (C)	2	1292.48	646.24	1.34	0.2799
Error	26	12559.84	483.07		
Level (L)	1	2793.69	2793.69	4.28	0.0589
Error	13	8475.89	651.99		
Memory (M)	1	760.60	760.60	0.74	0.4065
Error	13	13433.52	1033.35		
Density (D)	3	134308.32	44769.44	210.77	0.0000
Error	39	8283.96	212.41		
C × L	2	2431.18	1215.59	4.26	0.0251
Error	26	7414.31	285.17		
C × M	2	1329.90	664.95	3.27	0.0539
Error	26	5279.88	203.07		
C × D	6	1581.89	263.65	1.26	0.2871
Error	78	16361.46	209.76		
L × M	1	10953.50	10953.50	42.86	0.0000
Error	13	3322.28	255.56		
L × D	3	238.79	79.60	0.27	0.8479
Error	39	11571.72	296.71		
M × D	3	578.32	192.77	0.36	0.7854
Error	39	21146.13	542.21		
C × L × M	2	0.01	1101.17	4.53	0.0206
Error	26	0.93	243.27		
C × L × D	6	0.16	858.90	4.84	0.0003
Error	78	1.97	177.46		
C × M × D	6	0.45	558.38	2.67	0.0210
Error	78	2.64	209.50		
L × M × D	3	0.73	4733.89	26.03	0.0000
Error	39	1.26	181.84		
C × L × M × D	6	1308.52	218.09	1.08	0.3791
Error	78	15684.97	201.09		

C = Coding   L = Level   M = Memory   D = Density

coding types in the 14-symbol density display within the no-memory condition which tested search and identification performance. Figure 9 shows the mean response times for each coding type in the no-memory condition for the 14-symbol displays. The color-shape-coded condition had significantly lower response times than either the shape-only or color-only coded conditions.

There are other significant findings that are not related to coding type. The time to search, identify, and sequence the aircraft increased as density levels increased (figure 10). For all coding types in the no-memory condition, response time for completing the sequencing task was higher when both altitude and speed were encoded on the displayed symbols than when altitude alone was presented (figure 11). This effect was reversed for the memory condition. When retention was necessary, the length of time for subjects to sequence the craft was longer when altitude was presented alone compared to the length of time when both altitude and speed were encoded on the display.

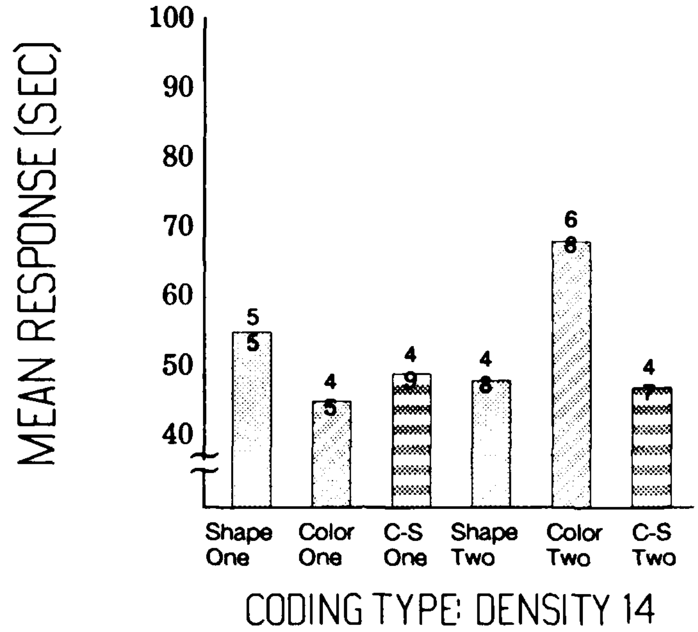

Figure 8. Mean response time for coding type in one and two levels of encoding at the 14-symbol density level.

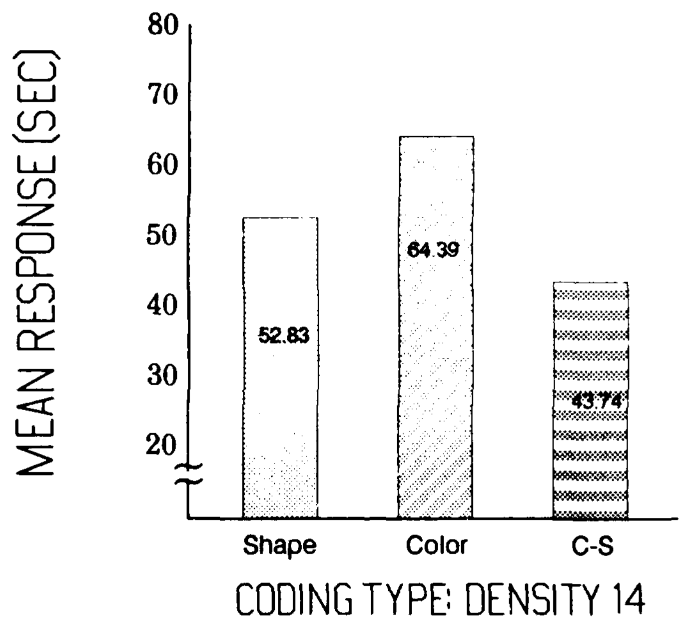

Figure 9. Mean response time as a function of coding type in the no-memory condition at the 14-symbol density level.

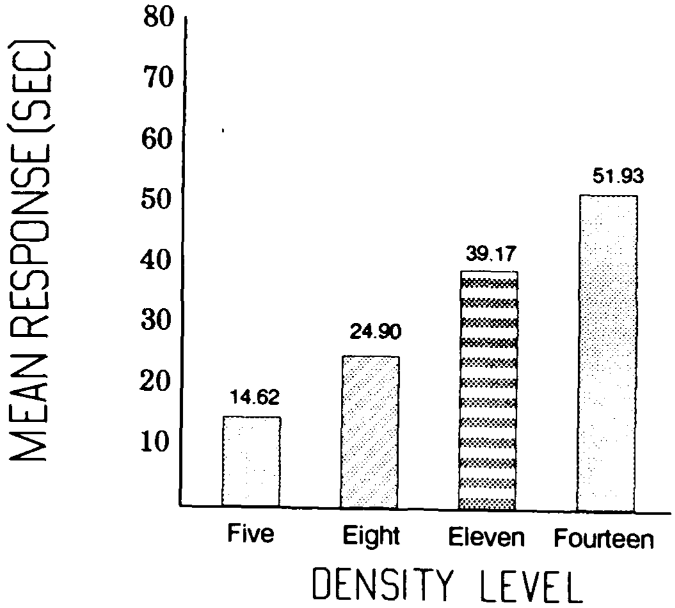

Figure 10. Mean response time as a function of density level.

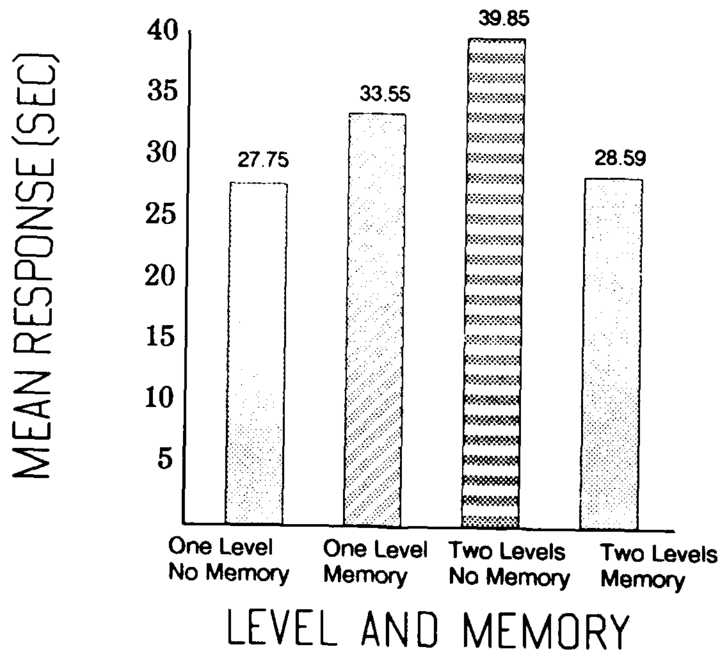

Figure 11. Mean response time for memory and no-memory condition with one and two levels of encoding across all coding types.

ADDITIONAL FINDINGS

A Pearson Product-Moment correlational analysis was performed to determine if there was any relationship between subjects' accuracy scores and the time needed by subjects to complete the task. No correlation was present. There was no relationship between the length of time subjects needed to complete the task and how accurately subjects performed the task. The subjective questionnaires were analyzed to determine subjects' display preference. Seventy percent of the subjects preferred the color-shape-coded condition for remembering encoded information. An analysis of variance was conducted to determine the existence of an order effect for all 14 subjects. No order effect was present.

SUMMARY OF MAJOR FINDINGS

Significant differences in accuracy scores between coding types occurred in the memory condition (recall accuracy) for the 8- and 11-symbol density displays. Recall accuracy in the 8- and 11-symbol density displays was superior in the color-shape-coded condition to either shape or color coding alone for both levels of encoding. In addition, recall accuracy was significantly higher in the color-coded condition and the color-shape-coded condition than recall accuracy with shape coding alone when only altitude (one level of encoding) was presented on the display.

Significant differences in response times between coding types occurred in the 14-symbol display compositions. When memory/no-memory conditions were pooled, the interaction between coding type and levels of encoding showed that response time in the 14-symbol density levels was significantly reduced for the color-coded condition when altitude alone was encoded on the symbol. Differences between coding types within memory- and no-memory conditions were analyzed. The significant differences in response time between coding types occurred in the no-memory condition. Response time in the 14-symbol density level was significantly lower for the color-shape coded condition than response time with the other coding types. No correlation was found between accuracy scores and response times. Accuracy scores were not affected by the length of time subjects took to complete the task.

DISCUSSION

It was hypothesized that subjects would perform the sequencing task more accurately when color was used as a primary (color-coded condition only) or redundant code (color-shape-coded symbols) than when shape coding was used alone. Accuracy scores were improved for the color and color-shape-coded conditions for one level of encoding where one color per symbol was presented on the display. However, subjects' accuracy performance on the sequencing task deteriorated when color was the primary code for two levels of encoding when two colors per symbol were presented on the display.

Luder and Barber (1984) theorized that color is processed in a parallel manner while shapes are processed serially. If true, the reason for higher accuracy scores for the color conditions in one level of encoding (one color on each symbol) could be due to this parallel processing. Accuracy performance may have deteriorated for color cod-

ing alone with two levels of encoding because subjects might have used serial processing to remember the two bits of information. If color is normally processed in a parallel manner and subjects had to attempt to process color-coded information serially (as in two levels of encoding), interference in cognitive processing of the encoded information may have caused a decrease in accuracy performance.

The two colors on one symbol did not degrade accuracy for the color-shape-coded condition with two levels of encoding. In the subjective questionnaires, subjects implied that they used color coding on one dimension (either altitude or speed) and shape on the other dimension. The advantage of parallel processing may still have prevailed with the subjects using parallel processing for color to encode either altitude or speed, while using serial processing with shape for the other coding dimension.

Subjects were expected to remember information better in the primary and redundantly color-coded conditions than in the shape-coded condition. Differences in accuracy between coding types within the memory condition existed in the 8- and 11-symbol density displays. Accuracy performance on the sequencing task was significantly improved for the color-shape-coded condition, as well as the color-coded condition alone, when subjects had to remember the altitude for 8 or 11 symbols with one level of encoding. These results support both Meister's (1984) and Neil's (1980) conclusions. Meister (1984) indicated that color coding is helpful when the operator's task is complex and color is logically related to the task in higher density displays. Neil (1980) concluded that color assists the operator in keeping track of critical information. It was necessary for subjects to remember critical information to perform the complex sequencing task in the present experiment.

The reviewed literature was inconsistent concerning the effectiveness of redundant color coding compared to color coding alone. Krebs et al. (1978) indicated that redundant coding is superior to coding on a single dimension. Saenz and Richie (1979) found no difference in performance between color as a primary code and color as a redundant code. The latter finding was duplicated in the present experiment when only one color was presented on the symbol. However, the opposite effect was noted when two colors were presented on each symbol. Retention for the 8- and 11-symbol density displays was superior in the color-shape-coded condition over retention with shape alone or color alone for two levels of encoding when subjects had to remember both altitude and speed. For two levels of encoding, color as a redundant code, did aid retention.

Krebs and Wolf (1979) pointed out that color does not aid the operator when the display is uncluttered. This was confirmed when no differences existed in retention between coding types in the 5-symbol density displays. Subjects remembered the encoded information and performed the task accurately with all coding types.

Recall accuracy was poor for all subjects in the 14-symbol display compositions with all coding types. Most subjects were unable to remember even 5 symbols in the proper sequence when 14 symbols were presented on the display. Probably sensory overload occurred when subjects attempted to remember encoded information on 14 symbols. Many subjects reported that 14-symbol displays contained too much information for effective recall. Neither color nor shape aided retention when subjects attempted to recall the altitude, or altitude and speed, to sequence 14 aircraft.

Since color, as a redundant code, aided retention in the displays containing 8 or 11 symbols for two levels of encoding, it is concluded that the proper use of color coding on displays can increase the amount of information retained by humans. Thus, operator performance may be improved on information displays such as air-traffic control and tactical displays with the addition of color-coded symbols.

Overall, color and the color-shape-coded conditions significantly improved response times for one level of encoding in the 14-symbol density levels across memory/no-memory conditions. In addition, when recall was unnecessary (no-memory), the color-shape-coded condition reduced response times on the 14-symbol display composition for both one and two levels of encoding. These findings were consistent with results of earlier research that indicated color coding decreases search time in search and identification tasks for complex displays (Cahill and Carter, 1976; Christ, 1975; Krebs and Wolf, 1979; Man Factors, Inc. 1980; Meister, 1984).

CONCLUSIONS

The following conclusions resulted from this study:

(1) Color, used appropriately for coding information on displays, increases the amount of information operators remember.

(2) Color, as a single coding dimension, aids retention when one color is used per symbol.

(3) Overall, color, as a redundant code, helps operators to remember encoded information on as many as 11 displayed symbols, even when two bits of information are encoded on each symbol. Operators can remember and use color-coded information to perform a related task.

(4) Overall, accuracy and response time in the combined color- and shape-coded condition were superior to the shape-coded condition alone.

(5) Sensory overload appears to occur when subjects attempt to remember encoded information on 14 symbols.

(6) Color, as a redundant code, can decrease response time in higher density displays.

RECOMMENDATIONS

Based on the above findings, the following recommendations are made for the use of color on information displays:

(1) Color-coded symbols should be implemented in information displays where operators need to keep track of critical information.

(2) Only one color per symbol should be used.

(3) Operators of information displays should not be required to remember encoded information on 14 or more symbols at one time. For example, an individual air-traffic controller should not control 14 or more aircraft at one time. Because this

experiment used discrete density levels of 5, 8, 11, and 14 symbols, we do not know if color-coded information continues to aid retention on 12 or 13 symbols or if sensory overload occurs.

FUTURE RESEARCH

Further research is needed to pinpoint exactly which information is detected, identified, and retained more effectively with color-coded symbols on information displays. The optimal number of colors and choice of colors on displays and the optimal number of dimensions to be color coded needs to be investigated to determine precisely how color coding can help operators remember critical information. The effectiveness of color-coded information on targets needs to be studied when other symbols on the display may act as distractors.

Many of the air controllers, who volunteered as subjects, suggested that the software program created for this experiment should be investigated for use as a screening test for potential air controllers. There appeared to be a correlation between air-controller's performance in the experiment and their performance on the job. A longitudinal study is necessary to determine the validity of this software program as a screening measure.

GLOSSARY

ASW – Antisubmarine Warfare

ATC – Air-Traffic Control

Coding Type – Refers to type of coding that was used to encode altitude and speed on the displayed symbols.

Cognitive – Involves the act or process of knowledge. Cognition includes imagining and judging as well as perceiving and reasoning (Marx & Bunch, 1977).

Color Coding – Color is used to encode all information on each symbol.

Color–Shape Coding – Both color and shape are used to encode the altitude or altitude and shape on each symbol.

CRT – Cathode Ray Tube

Density Level- Refers to the number of symbols that were presented on the displays.

EEC – Eurocontrol Experimental Center

FACSAC – Fleet Area Control and Surveillance Facility

Flight Data Strip – Hardcopy that lists current flight data for departing, arriving, and enroute aircraft. Information such as call signs, aircraft types, computer identification numbers, flight routes, and applicable times are listed.

Level of Encoding – Refers to the amount of information that is encoded on each symbol. (See one level of encoding and two levels of encoding for further definitions).

Memory Condition – Subjects had to remember the altitude or altitude and speed to perform the sequencing task.

No–Memory Condition – Subjects were tested on search and identification performance.

NTDS – Naval Tactical Display System

One Level of Encoding – Only altitude was encoded on each displayed symbol.

Parallel Processing – Information that is processed by the human simultaneously in its totality.

Primary Code – One dimension such as color used to encode information.

Redundant Code – Two dimensions such as color and shape used to encode information.

Sequencing Task – This task required subjects to number aircraft on the display according to altitude,or altitude and speed in the order which the planes would approach the entry area for landing.

Serial Processing – Items are consecutively processed by the human. In Western culture, humans usually process information from top to bottom and from left to right.

Shape Coding – Shape is used to encode all information on each symbol.

Two Levels of Encoding – Both altitude and speed were encoded on each displayed symbol.

Working Memory – Includes cognitive units activated from longterm memory, new items, and an internal model of the immediate environment (Murphy & Mitchell, 1984). That is, working memory includes items remembered for a long time, new items just presented, and an understanding of the situation.

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APPENDIX A

INSTRUCTIONS FOR SUBJECTS

INSTRUCTIONS

The purpose of this research is to determine if color on CRT displays can help air-traffic controllers remember information about displayed aircraft. You will be viewing displays which are similar to ATC displays. In figure 1, you can see a sample of the type of display that will be shown to you. The parallel lines on the right side of the display represent the entry to the landing area.

In some displays, both the altitude and speed of the aircraft will be presented. In other displays only altitude information will be presented.

The four altitude levels are

(1) Below 10,000 feet.

(2) 10,001 to 20,000 feet.

(3) 20,001 to 30,000 feet.

(4) Above 30,000 feet.

The four speed levels are

(1) Less than 200 knots.

(2) 201 to 300 knots.

(3) 301 to 400 knots.

(4) Above 400 knots.

You will view three different types of displays. In each type of display, shape and/or color is logically related to the altitude and speed level of aircraft. In one type of display, the shape of the symbol will denote the altitude level of the aircraft (figure 2). You will notice as the altitude rises the number of corners on the symbol increases (e.g., the symbol with the lowest altitude has no corners (circle) while the next altitude has 3 corners (triangle), the next highest has 4 corners (square), and the highest altitude has 6 corners (polygon)). When speed, aiong with altitude information, is presented on the display, the shape of the inner symbol denotes the speed level (figures 3 and 4). You will note as the speed increases, the number of lines inside the symbol increase, (e.g., the slowest speed is indicated by 1 line (1); the next fastest speed by 3 lines (Y); the next fastest speed by 4 lines (+); and the fastest speed has numerous lines (*)).

In the second type of display, all of the symbols will have the same shape. Only color will be used to denote the altitude level of the craft (figure 5). The darkest color indicates the lowest altitude. As the colors lighten, the altitude rises so that red denotes the aircraft at the lowest altitude; orange indicates the craft at the next highest altitude; yellow indicates craft at the next level; and white indicates the aircraft is flying at the highest altitude. When speed is presented on the display, the color of the lines within the symbol indicates the speed level (figures 6 and 7). As these colored lines lighten, the speed increases. Purple indicates the craft is flying at the lowest speed; dark blue denotes the aircraft is flying at the next speed level; and light green indicates the aircraft is flying at the fastest speed.

In another type of display, both color and shape will be used to denote craft altitude and speed. The symbols will have the same shapes and their connotations as the first type of display, and the same colors and their connotations as the second type of display (figures 8 and 9). These three types of displays will not necessarily be presented in this order.

After you view a display for a short period of time, you will hear a beep, and then you will be required to number the planes in the order they would approach the entry to the landing area. In half of the tasks, the symbols will be replaced by solid diamonds and you will be required to remember the altitude, or altitude and speed information about the symbols in order to perform the sequencing task. You will number the the craft in the order that they would approach the landing area by placing the cursor (a cross) on the middle of the symbol and pressing any button on the mouse. The mouse pad is located by the display. You move the cursor on the display by moving the mouse on the mouse pad. The cursor must be centered on the symbol before you press a button on the mouse. The number "1" will appear by the first symbol after you press the button on the mouse. You then place the cursor on the next aircraft that would approach the landing area and press any button on the mouse. The number "2" will then appear. You follow this procedure for all the craft on the display. If you forget the altitude or speed of any of the craft during the sequencing task, you will have to guess the sequence before the next scenario will be displayed. If you think you have numbered the planes in the correct sequence the first time and you do not wish to make any changes, then move the cursor to the box marked "No" and press any button on the mouse.

If you make an error while sequencing the planes, you can only erase the last number placed on the symbol. Then you may erase the number preceding that number. You are only allowed to erase up to the last 3 numbers on the sequenced aircraft. For example, if you sequence 4 planes on the display and then find another craft that should have been placed in the sequence earlier, you may erase number 4, then number 3, then number 2; but you will not be allowed to erase number 1. You just place the cursor on the middle of the symbol and then press any mouse button and the number will be deleted on that symbol. You follow this same procedure for the preceding 2 numbers if they are to be erased. You can then reorder the sequence of the aircraft simply by following the same procedure for numbering the aircraft as previously stated. You must number all the planes on the display in order to continue the experiment. If you miss even one symbol, the display will remain on the screen until that plane is numbered. When you finish prioritizing all of the aircraft for entry into the landing area, a message will ask you if you wish to correct the sequence. If you think you have sequenced the planes incorrectly, you may renumber the aircraft. Just move the cursor with the mouse to the box marked "Yes" and press any button on the mouse. Your orginal white numbers will remain beside the symbols. As you sequence the planes for the second time, the new numbers will appear printed in red. You will only be allowed one chance to resequence the planes. Then, the next scenario will be displayed.

We do not expect you to remember the altitude and speed of all the planes in the displays that contain many symbols. Please be as accurate as possible but don't be frustrated if you do not complete each task with 100-percent accuracy because it is not expected.

The following three factors will be used in this order of priority to sequence aircraft for entry to the landing area:

(1) Altitude,

(2) Speed, and

(3) Distance to the right side of the display, where the entry area is located.

Altitude has first priority. All the aircraft at the lowest altitude are selected for the approach to the landing area before craft at higher altitudes are selected. Speed is second in priority. If two or more symbols on the display have the same altitude, and if speed is also presented on the display, you are to prioritize these symbols by speed. For example, if two planes are flying below 10,000 feet, and one craft is traveling at less than 100 knots, and the other craft is traveling at 300 knots, you select the craft flying at 300 knots first. Proximity to the right side of the display is the third priority. If two or more symbols on the display have the same altitude and speed, you select the symbol closest to the right side of the display where the landing area is located. If speed information is not presented on the display, then use step number 3, distance to the entry area, as the next priority after altitude.

You will be required to learn the symbols before you are tested on any of the display types. You will need to achieve 100-percent accuracy on each of these training sessions. You will also be required to achieve 100-percent accuracy on the practice scenarios before testing begins in each condition.

PROCEDURE

The following summary shows how the order of priority for the planes:

For altitude displays only

1. You will view the display for a short period of time.
2. At the sound of the beep, begin sequencing the aircraft.
3. Select aircraft at the lowest altitude (below 10,000 feet).
4. If two or more planes are at the lowest altitude, select the closest craft to the right side of the display first, then the next closest, and so on.
5. After all the aircraft at the lowest altitude are numbered, follow the same procedure for the other three altitude levels (10,001 to 20,000 feet; then 20,001 to 30,000 feet; then the highest altitude (above 30,000 feet).

For altitude and speed displays

1. Study the display.
2. At the sound of the beep begin sequencing the aircraft.
3. Select aircraft at the lowest altitude (below 10,000 feet).
4. If two or more planes are at the lowest altitude, select the planes in order of speed so that planes traveling at the fastest speed (above 400 knots) enter the landing area first. Then select craft flying at the lowest altitude at speeds of 301 to 400 knots; then 201 to 300 knots; then craft at the lowest altitude with the slowest speed (less than 200 knots).
5. If two or more planes have the same altitude and speed, then select the closest planes to the right side of the display first.
6. After all the craft at the lowest altitude are numbered, follow this same procedure for the other 3 altitude levels.

NOTE: CRAFT AT THE LOWER ALTITUDES ENTER THE LANDING AREA FIRST. SPEED IS THE REVERSE OF ALTITUDE CRAFT WITH FASTER SPEEDS ENTER THE LANDING AREA BEFORE CRAFT WITH SLOWER SPEEDS (e.g., LOOK FOR THE CRAFT WITH THE LOWEST ALTITUDE TRAVELING AT THE FASTEST SPEED FIRST). REMEMBER! IN THE COLOR CONDITION, THE DARKEST COLOR INDICATES THE LOWEST ALTITUDE AND LANDS FIRST AND THE LIGHTEST COLOR THAT INDICATES THE FASTEST SPEED LANDS FIRST (e.g, AN AIRCRAFT WITH A RED ALTITUDE LEVEL (BELOW 10,000 FEET) AND A GREEN INNER SYMBOL (INDICATING A SPEED GREATER THAN 400 KNOTS) LANDS FIRST).

You will receive a performance score after you finish each test condition and your total score at the end of the experiment. There are 456 maximum points for this experiment. These scores are totaled for your personal feedback. Do not expect to obtain a perfect score. Please be as accurate as possible. Thank you for donating your time and effort to this study.